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Predictive Understanding of the Oceans' Wind-Driven Circulation on Interdecadal Time Scales

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We provide here the final report corresponding to the physical part of this project. This part was directed by the P.I., Michael Ghil, at UCLA. The P.I. and collaborators, at UCLA and in France, have improved their understanding of mid-latitude atmospheric phenomena influenced by thermal oceanic fronts. They have also deepened the understanding of decadal variability of the oceans' double-gyre circulation. Prof. Roger Temam at Indiana University directed the mathematical part of the project, and the final report for this part was submitted in 2007. The physical part suffered in its third year from under-performance of a post-doc and thus required a no-cost extension. The results during the fourth and final year were more than satisfactory, as reported below. The final result is an emerging theory of the North Atlantic Oscillation and its downstream effects over Europe, the Mediterranean, and the Middle East.

1. Introduction

We have worked on two fronts. First, following the results obtained by Feliks et al. (2004; FGS-BT hereafter) a new and ambitious research program has been developed to study, in a systematic way, the influence of oceanic thermal fronts on the mid-latitude atmosphere. In particular, this program focuses on a hierarchy of models of increasing complexity, from barotropic quasi-geostrophic (QG) equations to full, coupled general circulation models (GCMs).

Second, we have continued our work on the low-frequency variability (LFV) of the double-gyre, wind-driven circulation. In particular, we have focused on the recently discovered phenomenon of quantization of the low-frequency dynamics of oceanic jet streams into a discrete set of spectral peaks, and on fully coupled ocean-atmosphere models of the North Atlantic basin and surrounding continents. Dijkstra and Ghil (2005) reviewed previous results on the double-gyre circulation.

2. Influence of oceanic thermal fronts on atmospheric LFV

We recall here some important results obtained by FGS-BT. In this earlier work we investigated the influence of strong thermal oceanic fronts on a barotropic atmosphere above it. Strong oceanic fronts were shown to be able to inject a significant amount of potential vorticity (PV) into the atmosphere and thus induce persistent atmospheric eastward jets.

The FGS-BT model uses a highly idealized atmospheric marine boundary layer (AMBL) characterized by a homogeneous potential temperature T throughout, and a pressure that decreases linearly with height. The linearized equations of motion in this simple AMBL can be solved analytically for the horizontal velocity field, and yield the vertical velocity at the top of the AMBL.

The resulting Ekman pumping induced by an oceanic thermal front is strong enough to produce a robust atmospheric jet in the free atmosphere above the AMBL. The instabilities of this eastward jet are able, in turn, to generate intraseasonal variability in this model's barotropic free atmosphere.

2.1. LFV in a baroclinic atmosphere over an oceanic thermal front

Feliks et al. (2007; FGS-BC hereafter) have continued the work of FGS-BT in studying the behavior of an atmospheric QG model, forced by a strong oceanic thermal front. We have extended the earlier barotropic study by considering a two-mode baroclinic free atmosphere.

The atmospheric jet induced by the idealized oceanic front is still quite vigorous, in spite of the additional, baroclinic instabilities associated with it. In fact, we find westward propagating barotropic instabilities with periods of 5–80 days, like in FGS-BT, as well as ultra-low-frequency variability of 6–8 months. The later variability arises from baroclinic instabilities in the form of standing-dipole anomalies. We also observe in the model northward-propagating anomalies, i.e. roughly perpendicular to the oceanic jet, with a period of 2–3 months. These mixed barotropic-baroclinic instabilites might be linked to the observed North Atlantic 70-day oscillation documented by Plaut and Vautard (J. Atmos. Sci., 1994) in atmospheric data sets.

2.2. Atmospheric LFV over a realistic SST front

Barotropic and baroclinic models have also been forced by winter-mean sea surface temperatures (SSTs) from the French ocean-data assimilation project Mercator, for the North Atlantic, at a fairly high resolution (20 km; see http://www.mercator-ocean.fr). This part of the work is conducted in collaboration with a French team, led by Hervé Le Treut, Director of the Laboratoire de Météorologie Dynamique (LMD) in Paris, at no extra cost to the DOE-sponsored project. The main link between our project team and this team is a post-doc whose research focuses on the topic at hand, Dr. Sidonie Brachet, supported by French funds. Preliminary results for a barotropic atmosphere encouraged us to pursue the same experiment using Mercator SSTs with a baroclinic atmosphere.

In the barotropic set-up, a periodic domain of size 6000 km x 3000 km was considered. To avoid the spurious effects of Rossby waves reentering the domain by periodicity, we performed the baroclinic experiments using open-boundary conditions. The key idea is to impose so-called radiation boundary conditions on the potential vorticity at the western bounday, in order to filter out wave reflections as well. We use, in fact, a more sophisticated approach, namely a two-dimensional (2-D) Orlansky method (cf. Marchesiello et al., 2001). The results using this method indicate that baroclinic instabilities do not destroy the eastward jet that forms over the Gulf Stream front and the atmospheric LFV obtained is comparable to the one found in the barotropic case.

2.3. Atmospheric GCM results with LMD-Z zoomed over the Gulf Stream

To confront the theoretical results obtained by FGS-BT and FGS-BC with observations, we carried out atmospheric GCM simulations over the Gulf Stream region, using both climatological SST and Mercator data. This part of the work is conducted using the LMD's atmospheric GCM, called LMD-Z, in close collaboration with S. Brachet, F. Codron, H. Le Treut, P. Le Van, and L. Li from the LMD in Paris. LMD-Z is a full-blown GCM based on discretizing the primitive equations on a latitude-longitude grid; it has the important feature of allowing a zoom-in capability over an oceanic region of interest, hence the 'Z' for "zoom" in the model's acronym. As a first step, we considered an idealized SST front, as in FGS-BT and FGS-BC.

FGS-BT showed that high resolution was crucial in simulating the effect of an SST front on the atmosphere. It is the lack of sufficient resolution in typical simulations with atmospheric GCMs that contributes to the long-standing controversy about the size and significance of climate impacts due to mid-latitude SST anomaly. We chose therefore to study such impacts in the Gulf Stream region, where a sharp SST front is present; the zoom area is centered at (65 W, 40 N).

The model is vertically discretized on 19 hybrid sigma-pressure levels. We used a resolution of 3 degrees outside the zoom area and 0.5 degrees inside it, which yields a fairly satisfactory Gulf Stream front. In order to filter out the seasonal signal and thus isolate more easily the signals of interest, we followed Marcus et al. (J. Atmos. Sci., 1994, 1996) and implemented a perpetual forcing, based on the climaological fields for 15 February. To avoid spurious accumulation of snow cover at the North Pole and over the mountains, we imposed a constant ground humidity field.

Three simulations have been analyzed (Brachet et al., 2008):

(i) a control simulation with the climatological SST field and no zoom;
(ii) a control simulation with the climatological SST field, but zooming in on the area of interest; and
(iii) a simulation in which the SST front has been modified.

To evaluate the effects of a stronger gradient, we added a theoretical SST anomaly centered at (60 W, 40 N) given by

$f(T)= 2\cos(x)*(-8)\sin(y)$,

where x is the along-jet coordinate and y is perpendicular to it. This idealized Gulf Stream front has an axis inclination of 25 degrees to the zonal, eastward-pointing direction.

These 3 simulations are respectively 80, 872 and 872 days long. We studied in detail the last two simulations, and carried out spectral analyses of the resulting fields over the Gulf Stream region and an extended region that encompasses the first one. The time-averaged fields over the 3 levels that correspond to the AMBL (levels 17 to 19) and the 10 for the upper troposphere (levels 1 to 10) show that the jet stream is indeed reinforced around Eastern Greenland in the strong-gradient simulation. Even more encouraging is the fact that descending and ascending winds induced by the thermal front are much more pronounced in the simulation at high resolution (using the zoom) than otherwise, as suggested by the two FGS papers.

2.4. Conclusions

We have obtained remarkable similarities between observed intraseasonal oscillations over the North Atlantic and the oscillatory instabilities present in our hierarchy of three atmospheric models — barotropic (FGS-BT), baroclinic (FGS-BC) and GCM (Brachet et al., 2008) — all forced by an idealized steady Gulf Stream front.

1. In observations and all 3 models, the signal propagates northeastward.
2. The model instabilities are related to quasi-stationary Rossby waves, trapped by the atmospheric jet that is induced, through thermal Ekman pumping, by the Gulf Stream front.
3. Some of the model instabilities have similar spatio-temporal patterns, but with somewhat different periods, depending on the strength of the atmospheric jet and the model structure.

To the extent that the LMD-Z results will hold up under further scrutiny, the theory presented here would have predictive capabilities. It can also provide greater insight into the nature of ocean–atmosphere coupling at mid-latitudes and a deeper understanding of interannual NAO variability.

3. Interdecadal variability in the double-gyre circulation

3.1. Effects of the seasonal cycle on the double-gyre circulation

Sushama et al. (2007) studied the mid-latitude ocean's response to time-dependent zonal wind-stress forcing using a reduced-gravity, 1.5-layer, shallow-water model in two rectangular ocean basins of different sizes. The small basin is 1000 km x 2000 km and the larger one is 3000 km x 2010 km; the aspect ratio of the larger basin is quite similar to that of the North Atlantic between 20 N and 60 N. The parameter dependence of the model solutions and their spatio-temporal variability subject to time-independent wind stress forcing serve as the reference against which the results for time-dependent forcing are compared.

For the time-dependent forcing case, three zonal-wind profiles that mimic the seasonal cycle were considered in this study: (1) a fixed-profile wind-stress forcing with periodically varying intensity; (2) a wind-stress profile with fixed intensity, but north–south migration of the mid-latitude westerly wind maximum; and (3) a north-south migrating profile with periodically varying intensity. Results of the small-basin simulations show the intrinsic variability found for time-independent forcing to persist when the intensity of the wind forcing varies periodically. It thus appears that the physics behind the upper ocean's variability is mainly controlled by internal dynamics, although the solutions' spatial patterns are now more complex, due to the interaction between the external and internal modes of variability. The north–south migration of wind forcing, though, does inhibit the inertial recirculation; its suppression increases with the amplitude of north–south migration in the wind-stress forcing.

Model solutions in the larger rectangular basin and at smaller viscosity exhibit more realistic recirculation gyres, with a small meridional-to-zonal aspect ratio, and an elongated eastward jet; the low-frequency variability of these solutions is dominated by periodicities of 14 and 6–7 years. Simulations performed in this setting with a wind-stress profile that involves seasonal variations of realistic amplitude in both the intensity and the position of the atmospheric jet show the 7-year periodicity in the oceanic circulation to be robust. The intrinsic variability is reinforced by the periodic variations in the jet's intensity and weakened by those in meridional position: the two effects cancel, roughly speaking, thus preserving the overall characteristics of the 7-year mode.

3.2. LFV quantization in the double-gyre circulation

Simonnet (2005) has found that the low-frequency dynamics of the double-gyre circulation in large oceanic basins exhibits striking behavior that is nearly self-similar in nature. This behavior depends solely on the fact that the jet stream is able to penetrate far into such a basin. We show in an equivalent-barotropic QG model that the mere presence of interfacial and/or bottom stress, parameterized as Rayleigh dissipation, enables this eastward penetration. But the nearly self-similar nature of the LFV is far more general.

As the length of the jet increases, successive symmetry-breaking instabilities occur, with larger and larger wave numbers; this is shown numerically, as well as analytically. These symmetry-breaking bifurcations are physically explained by the existence of stationary Rossby waves. A key idea is that these stationary Rossby waves are enabled when their phase velocity balances their eastward advection by the oceanic jet stream. These waves are also responsible for subtler nonlinear effects, for instance they trigger the unfolding of low-frequency, asymmetric, oscillatory gyre modes and their associated quasi-homoclinic dynamics (Simonnet et al., 2005). These instabilities drive the flow on interannual-to-interdecadal time scales, depending on the length of the jet. A rigorous mathematical justification of these results is described next.

3.3. Real bifurcations in the 2-D linearized Euler-QG spectrum

We decided to report this work both in the mathematical part (conducted mostly at Indiana University) and in the physical part (conducted mainly at UCLA). Indeed, the mathematical results obtained in this work have a direct impact on the understanding of the low-frequency dynamics of the Gulf Stream and other oceanic jets. These results also shed additional light on the role played by "gyre modes" in the low-frequency dynamics of jet streams.

Based on earlier work by Lin (Commun. Math. Phys., 2004), we have investigated the behavior of the unstable spectrum of the linearized 2-D Euler equation in a bounded domain, as a function of the spectrum of a self-adjoint operator L_0 of Schroedinger type, when the size of the domain is increased. We showed that there exist, locally near the origin of the phase-parameter space, real eigencurves of both stable and unstable character, provided L_0 exhibits a codimension-1 bifurcation in the size parameter. The eigencurves $\epsilon(\lambda)$, where λ is the characteristic exponent of the unstable eigenmode and ϵ^{-1} is the length of the domain, behave quadratically in the neighborhood of the bifurcation and are either subcritical or supercritical. The difficulties of this work are related to the existence of an essential spectrum in the Euler equations and involve the asymptotic perturbation theory of linear operators (Kato, 1980).

This theoretical work, along with the numerical illustrations of its results, clearly indicates that the observed quantization of the low-frequency variability in QG models of the ocean and atmosphere is ultimately related to the spectral behavior of a Schroedinger class of operators. Stationary Rossby waves are just particular eigenmodes of such operators. These waves play a key role in driving the internal LFV of oceanic jets like the Gulf Stream through the so-called gyre modes. Hence this work provides a much deeper and comprehensive view of the nonlinear dynamics of mid-latitude ocean basins. Several exciting new mathematical questions are also being addressed in follow-up on this work.

4. No-cost extension and final results

In the final year of this DOE project, we pursued our theoretical and numerical investigations concerning the effect of thermal oceanic fronts on the mid-latitude troposphere. Significant advances were made in three different directions:
i) a coupled quasi-geostrophic (QG) model of the North Atlantic under realistic conditions;
ii) ocean data reanalysis of the North Atlantic region; and
iii) LMD-Z simulations over the Gulf Stream.
The results of (iii) are reported in subsection 2.3 above, for the sake of continuity. We report on items (i) and (ii) below.

4.1. Ocean data reanalysis and the North Atlantic 7–8 y oscillation

Low-frequency oscillations with a period of 7–8 years have been found in various oceanic and atmospheric fields from the North Atlantic, Europe and North America (Moron et al., Clim. Dyn., 1998; Dijkstra and Ghil, 2005, and references therein). Feliks et al. (2004, 2007) suggested a possible mechanism for the influence of interannual variability in the Gulf Stream's SST front on atmospheric LFV.

Their atmospheric model was forced by an idealized SST front. The intensity of the SST front had an interannual period that led to periodic behavior in the free atmosphere with the same period. The varying frontal strength induced an increase or decrease in the mean atmospheric jet speed. Two regimes alternated over the period of the forcing:

a) When the oceanic front and the atmospheric jet are both strong, a high-energy regime is obtained; large meanders and eddies develop along the jet axis, and the dominant oscillation has a period of about 70 days.

b) When the oceanic front and the atmospheric jet are both weak, a low-energy regime results. In this regime, small meanders develop along the jet axis, and the dominant oscillation has a period of about 25 days.

To further examine this hypothesis we have analyzed oceanic fields from the western North Atlantic in the rectangle (28N–42.5N, 80W–60W), between January 1958 and December 2007. The data were extracted from the Simple Ocean Data Assimilation (SODA) ocean reanalysis of Carton and Giese (Mon. Wea. Rev., 2008).

The mean sea surface height in SODA corresponds to the barotropic component of the Gulf Stream and exhibits a strong jet that flows along the East Coast of the United States, from the Florida Straits until the separation point at Cape Hatteras. The leading oscillatory mode of our Singular Spectrum Analysis (SSA; Ghil et al., Rev. Geophys., 2002) has a period of 1 year, and contains 12 % of the variance. The second oscillatory mode has a period of 7.8 years and contains 5 % of the variance. This second mode is characterized by a North-South oscillation of the mean Gulf Stream path, downstream of the separation point. The temperature field at a depth of 5 m corresponds to the SST and exhibits a similar oscillation. The role of this oscillation in the dynamics of the overlying atmosphere is under further study.

4.2. Coupled ocean-atmosphere models of the North Atlantic circulation

Mid-latitude interactions between the ocean and the atmosphere were also studied in a fully coupled mode. Simonnet et al. (2008) consider QG models of a dynamic ocean coupled with the atmosphere. After spin-up, the ocean exhibits a classical double-gyre circulation that interacts nonlinearly with the atmosphere through Ekman pumping.

The fixed oceanic front of the previous studies thus becomes a variable one, subject to atmospheric feedbacks. Several time scales now interact: these include the intrinsic variability of the double-gyre circulation, on interannual and interdecadal time scales (Simonnet, 2005; Simonnet et al., 2005), as well as atmospheric LFV, on intraseasonal and interannual time scales (Feliks et al., 2004, 2007).

The spatial scales differ as well: the spatio-temporal anomaly patterns in the atmosphere have much larger spatial scales than in the ocean. Our coupled model thus exhibits highly complex low-frequency dynamics that we are elucidating in greater depth and detail

We first consider a baroclinic, eddy-resolving ocean using a realistic bathymetry of the North Atlantic basin. It has a horizontal resolution of 10 km x 10 km, three layers in the vertical, and is forced by wind stresses from the Cooperative Ocean-Atmosphere Data Set (COADS), at a resolution of 1 deg long. x 1 deg lat. or by Hellerman and Rosenstein (J. Phys. Oceanogr., 1983) wind stresses at a resolution of 2 deg long. x 2 deg lat., We used no-slip boundary conditions and pushed the model into a highly inertial regime with a typical viscosity of 150 m^2/s. The ocean model exhibits a very realistic Gulf Stream that does separate at Cape Hatteras and extends beyond the Grand Banks.

The oceanic model is then coupled with the atmosphere as in Feliks et al. (2004, 2007), namely it is forced by the Gulf Stream's thermal front through the advected SST and associated Ekman pumping. The atmospheric domain is a periodic channel with two different settings, i.e. free-slip and radiative boundary conditions, respectively. The coupling yields a fairly strong atmospheric jet above the Gulf Stream front, with a speed of about 10 m/s. This jet exhibits intraseasonal as well as interannual variability, associated with atmospheric instabilities and the oceanic gyre mode, respectively.

The full coupling to the highly variable atmosphere significantly enhances the oceanic mesoscale turbulence, without substantially altering the ocean's intrinsic, interannual variability. Complete, detailed analysis of the coupled model variability is under way.

4.3. Conclusions

The no-cost extension of the project has greatly helped complete the results on the interdecadal variability in the North Atlantic's double-gyre circulation. This variability has been explored in both stand-alone and coupled mode, with very promising results. Several further publications will be completed and submitted soon, on the results outlined in sections 3 and 4 of this Final Report.

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